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Microwave radars deployed near the marine environment, e.g., shipboard and airborne radars, are subjected to sea return or sea clutter. In many instances, sea return for radars at large angles of incidence or small grazing angles (less than 15°) is of special importance.

This study examines the effects of better environmental inputs to an existing sea clutter model that has proven to be adequate for small grazing angles. Limitations in the existing model are described, improvements are suggested, and plans for improving the model are outlined and discussed.

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THE EFFECTS OF BETTER ENVIRONMENTAL INPUTS IN ESTIMATING SEA CLUTTER

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1. INTRODUCTION

Radar return from the sea, commonly known as sea echo or sea clutter, has been observed since the deployment of microwave radars to detect objects on or near the sea surface (Crombie, 1955). Considerable progress has been made in terms of understanding the basic physical processes which cause sea clutter. The basic mechanism involved is the interaction of electromagnetic waves (microwaves in this case) with the ocean surface. A comprehensive review of the subject is not given here but is found in Valenzuela (1978) and the recent work of Donelan and Pierson (1987) which gives an extensive review and references on this topic. Brief descriptions of the current models are given below.

Much of the work on the interaction of electromagnetic and ocean waves is targeted at remote sensing of the ocean, e.g., to extract oceanographical or meteorological data from the radar return. Here, we have the "inverse" problem of calculating the microwave backscattered signal if we are given the characteristics of the scattering surface, viz., the ocean surface. However, the basic scattering principles remain the same.

Few researchers have taken full advantage of the possible gain from incorporating better environmental data in estimating sea return. Because it is mainly the surface of the ocean which effects sea return, one would expect a more complete knowledge of the ocean surface and any environmental factors that influence its evolution to enhance the estimation of the sea clutter radar cross section. In the past, it was difficult to estimate or predict the waves in the open ocean short of using actual measurements. One usually assumes a certain fetch and duration together with any wind information to estimate the waves. With the advent of better ocean wave models and computers, one can predict many parameters of the open ocean to a fair degree of accuracy. Some of these parameters which can affect sea return are significant wave height, swell height, and one- and two-dimensional ocean wave spectra at points of interest. The information given by an accurate ocean wave model is definitely more comprehensive than the sparse local data which are usually obtained by a ship or a plane.

For example, a sea clutter model for radars operating at small grazing angles has been developed by the Georgia Institute of Technology (GIT model). This model employs only four environmental data inputs: the local wind speed, the local wind direction, the local average wave height, and a duct height constant if ducting is to be expected. In many cases, only the vector wind information is used as the input to the GIT model if wave growth is assumed to have reached an equilibrium state, which frequently may not be the case. One obvious improvement to the sea clutter model is to accept inputs from an ocean wave model. The wave model gives not only the local wave parameters but also data for areas around the radar site. Because the radar scans up to a fair distance from its site, the surrounding environmental factors should be more pertinent to the sea return than the local data. A simple but important improvement to the sea clutter model is to use the wave direction in the sea clutter model, while previously only the local measured wind direction was used. This is important because sometimes the wind and wave directions are not the same, and the sea return is likely to be more dependent on the wave direction than the wind direction. This result agrees with some qualitative data.

Various other improvements to the sea clutter model can be made. Because the wave model gives information on the ocean wave spectra (with a spectral model for the capillary waves), it can be used as the input to more sophisticated sea clutter models such as the slightly rough or composite models (see later sections). Further work on the combined ocean-wave and sea clutter model may include using some recent findings in wave breaking which is believed to be the cause of spiky sea return of high resolution radars. The ocean wave model (see section 3) currently under use also has a shallow water wave option which can be used in regions of shallow water, such as an enclosed or semi-enclosed basin.

Because sea clutter is the result of microwave scattering off the ocean surface, and the characteristics of the ocean surface are affected by numerous environmental factors, it is clear that to have a better understanding of sea clutter it is absolutely essential to focus on the environmental effects on radars and in particular, to understand the key environmental factors which give rise to sea clutter. Another important point to keep in mind is that the ocean surface is always changing and any attempt to track or cancel sea clutter via signal processing schemes must also be adaptive. However, one must utilize the correct physics for sea clutter, or at least the correct statistics, to devise any meaningful adaptive schemes. This report focuses on the effects of better environmental inputs in estimating sea clutter and does not address new signal processing techniques or new detection models, although some of these topics are inter-related. A step by step plan is laid out to evaluate the possible improvement in estimating sea clutter.

2. SCATTERING MODELS

There are a number of sea clutter models or scattering models which relate the microwave backscattered signal with certain parameters of the radar and the environment. Five main models are briefly described below together with their limitations. Emphasis is placed on the first model described later because it is the most commonly used model for radars operating near grazing angles (less than 15 degrees).

Other models, such as the specular-point, the slightly-rough Bragg scattering, and the composite-surface models, although more complicated than the GIT model, are still tractable and based upon more solid physical principles. However, these models are usually mathematically involved which is why they have been excluded from common operational use. These three models cover a wide range of angles of incidence which can vary from 0 to 70 degrees or so. However, these models do not give good results at extreme angles of incidence (small grazing angles).

Various models have evolved by combining or extending one or more of the above mentioned models to fit the necessary application needs. Some of these models, such as one which incorporates composite-surface and wedge scattering models, claim success at calculating the normalized radar cross section at grazing incidence for the ocean driven by high winds.

2.1 Georgia Institute of Technology (GIT) Sea Clutter Model

Background

This model was developed by the Engineering Experiment Station at the Georgia Institute of Technology. Descriptions of the model can be found in Horst et al. (1978) and Ewell et al. (1979). Because a complete theoretical description of the microwave backscattering process from the ocean surface near grazing incidence is complicated by the presence of the forward-scattered interference field and by the properties of the ocean surface itself, attempts to model this process have met with varying degrees of success. At the time of development of the GIT model, even relatively complete treatments based on the composite-surface model or microwave Bragg scattering did not yield reasonable agreement with experimental data over the necessary wide range of environmental conditions and operating frequencies. Thus, a combination theoretical and empirical model for radar sea clutter was developed at GIT for use in radar performance prediction, utilizing theoretical prediction of dependences, but with experimental data used to determine nominal values for certain critical constants.

The variables of the GIT sea clutter model are listed in Table I and the sea clutter model equations are given in Table II. The model calculates the average clutter cross section per unit area (σ^o) which depends on the environmental conditions (i.e., average wave height, wind speed, and wind direction), location of the radar (antenna height, range), propagation conditions (effective earth radius, duct height), and radar parameters (wavelength, polarization). Furthermore, the average clutter return seen by a radar depends not only on the normalized clutter cross section σ^o, but also on the radar resolution size, which is a function of pulse width, beamwidth, and range.

Table 1. Variables of the Sea Clutter Model.

Symbol	Definitions (Units)	Restrictions
h_a	Radar antenna ht (ft)	-
R	Range (nmi)	-
A_e	Effective earth radius (nmi)	-
λ	Radar wavelength (ft)	0.1 to 1
h_d	Duct height (ft)	-
α	Incidence angle (radians)	0.001 to 0.2
h_{av}	Average wave ht (ft)	0.25 to 13
Φ	Angle between boresight & upwind (radians)	0 to π
V_w	Wind speed (knots)	3 to 30
τ	Pulse width (sec)	5×10^{-8} to 2×10^{-6}
θ_a	3 dB azimuth beamwidth (One Way) (radians)	-
c	Speed of light (m/sec)	2.998×10^8
σ^o	Average clutter cross section per unit area (dB)	-
A_c	Area of radar resolution cell (dBsm)	-
σ_c	Average clutter cross section (dBsm)	-
A_i	Interference factor	-
A_u	Upwind/Downwind factor	-
A_w	Wind speed factor	-

Table 2. Sea Clutter Model Equations.

$$\alpha' = h_a/6076R - R/2A_e$$

$$\alpha = \sqrt{\alpha'^2 + (\lambda/4h_d)^2}$$

$$\sigma_\phi = (4.4\lambda + 5.5)\,\alpha\, h_{av}/\lambda$$

$$A_i = \sigma_\phi^{\,4}/(1 + \sigma_\phi^{\,4})$$

$$A_u = \exp\{0.3(\cos\Phi)(1 - 2.8\alpha)(\lambda + 0.05)^{-0.4}\}$$

$$qw = 1.7(\lambda + 0.05)^{-0.4}$$

$$V_w = 10.47\, h_{av}^{+0.4}$$

$$A_w = [V_w/(1 + V_w/30)]^{qw}$$

$$\sigma^o_{HH} = 10 \log[1.2 \times 10^{-6} \lambda\, \alpha^{0.4}\, A_i A_u A_w]$$

$$\sigma^o_{VV} = \sigma^o_{HH} - 1.05\, \ell n(h_{av} + 0.05) + 1.09\, \ell n(\lambda) + 1.27\, \ell n(\alpha + 0.0001) + 9.65$$

$$A_c = 10 \log \left(\frac{1852\ R\ \theta_a\ c\,\tau}{2\sqrt{2}} \right)$$

$$\sigma_c = \sigma^o + A_c$$

Some sample comparisons of the GIT model with actual radar data can be found in Figures 1 to 4. The figures are taken from Horst et al. (1978). The solid lines in the figures are given by the sea clutter model while the experimental data are given by the various symbols as shown. The sea clutter model results compare reasonably well with the experimental data except maybe for the low average wave height cases, e.g., $h_{av} = 0.15$m.

Limitations and Possible Improvements

Because this is a semi-empirical model, the range of applicability of the model is limited as given in Table 1. It would be interesting to examine the potential for improving this model with advances in other areas, such as ocean wave modeling or surface-based remote sensing techniques.

The main environmental input to the model is the wind velocity (speed and direction) as shown by the model equations in Table 2. According to the model equations, the average wave height is an independent variable. In practice, it is rarely measured or used as an independent input to the model because it is not as easy to measure as the wind velocity. An empirical relationship is often used instead to relate the average wave height to the wind speed. It should be obvious that the microwave scattering is effected by the ocean surface and not by the wind itself even though the main scatterers (mainly capillary waves at the air-sea interface) are generated by wind action. One prime example is the response of a calm sea surface to a light breeze. The water is initially marked by the random appearance of small, darkened, ruffled patches called cat's paws (Kinsman, 1965). These ruffled patches can give strong backscatter signals to a radar, even though the wave height remains small because it takes longer (time, wind duration, or fetch) for gravity waves to develop.

One obvious improvement to the GIT sea clutter model is the incorporation of inputs from an ocean wave model. An ocean wave model gives not only the local wave parameters but also data for areas around the radar site. Because the radar scans up to a fair distance from its site, the surrounding environmental factors should be more pertinent to the sea return than local data such as the local vector wind and wave height. Another simple but important improvement to the sea clutter model is the incorporation of the wave and swell direction in the sea clutter model. Currently, only the local measured wind direction is used. This is important because the wind and wave directions need not be the same, and the sea return is likely to be more critically dependent on the capillary and short gravity wave directions.

2.2 The Specular-Point Model

Background

This model calculates the scattered fields according to the Stratton-Chu integral equations (Stratton, 1941). Because these equations need the field values at the surface of the ocean, the surface geometry must be known to compute the scattered field. However, when the surface has a radius of curvature that is large compared to the wavelength of the incident microwave wavelength, the tangent-plane approximation can be used (i.e., the surface fields are approximated by the fields which would be present were a flat tangent plane set at each point along the surface). This is also known as the Kirchoff or physical optics method.

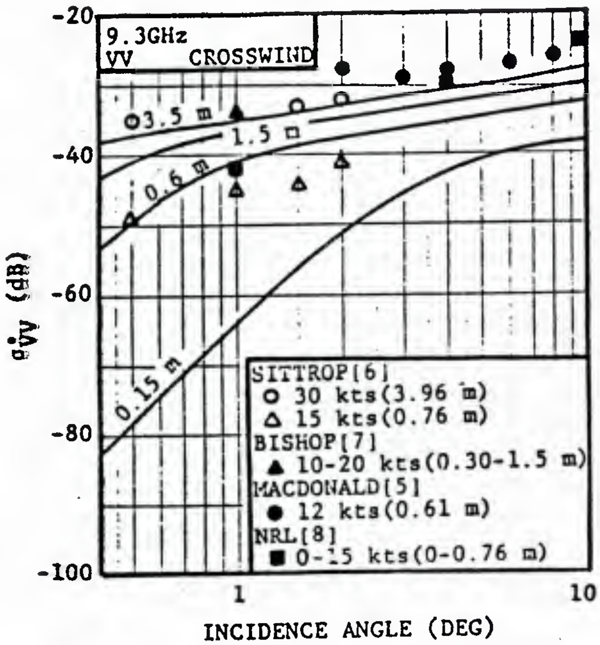

Figure 1 Comparison of σ°_{VV} data with GIT model predictions at X-Band

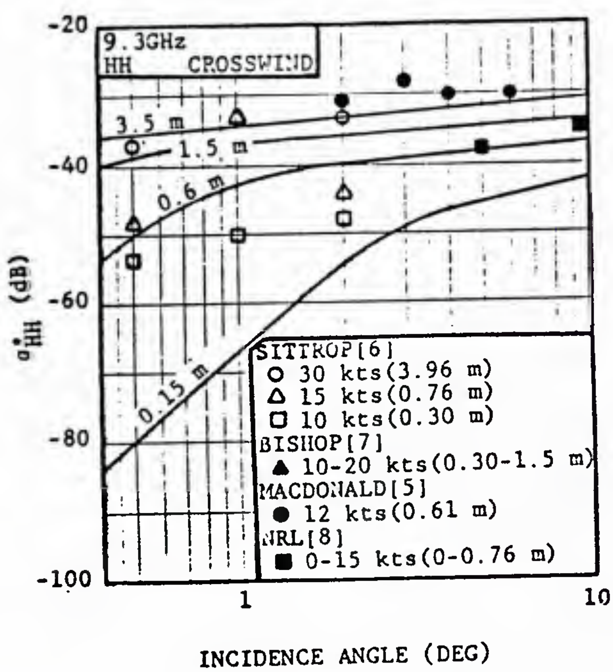

Figure 2 Comparison of σ°_{HH} data with GIT model predictions at X-Band

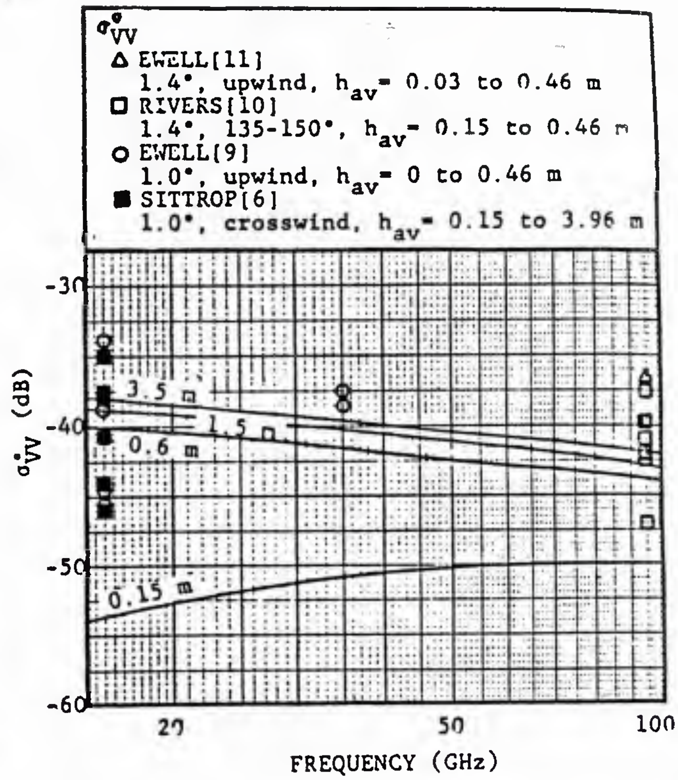

Figure 3 Comparison of millimeter wave σ°_{VV} data with GIT model predictions

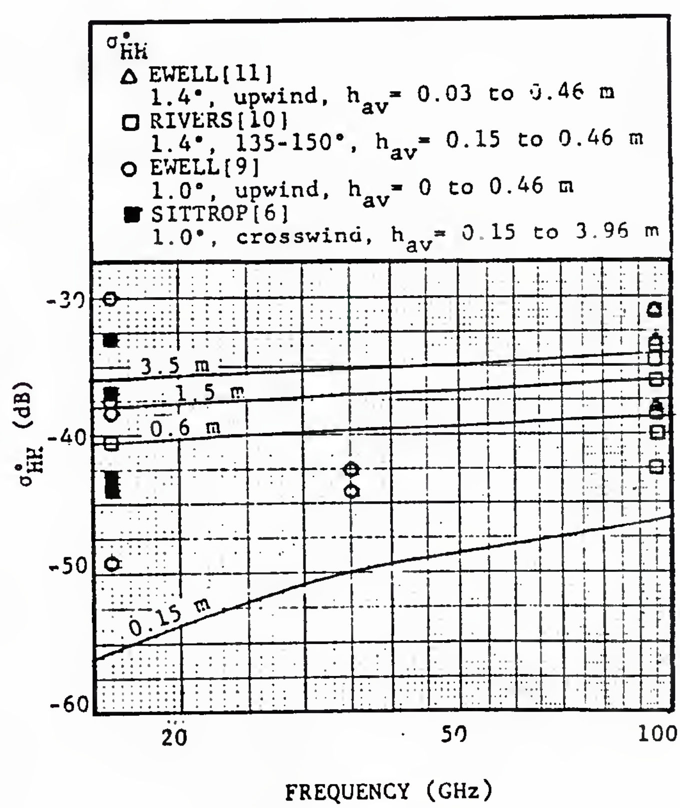

Figure 4 Comparison of millimeter wave σ°_{HH} data with GIT model predictions

Limitations and Possible Improvements

Within the framework of the specular-point model, there exist numerous specific models which are applicable to special cases, such as those given by Siegel (1958), Kodis (1966), and Barrick (1968). Because of the tangent-plane assumption, the specular model is generally believed to be limited to near normal incidence. However, recent work of Kwoh and Lake (1984) has shown that the specular contribution is found to be more important than generally expected, even at moderate to high incidence angles, and its source seems to be the specular facets in the turbulent wake and the capillary waves generated during breaking.

2.3 Slightly-Rough Bragg Scattering Model

Background

Crombie (1955) explained the backscattered radar spectra as being produced by the first-order diffraction patterns of short sea-wave grating of variable spacing. Wright (1966, 1968) established experimental evidence for a first-order scattering theory which can be applied to obtain sea clutter cross sections in terms of mean-squared height spectrum of the sea surface. This model gives good agreement with data for vertical polarization at P-, L-, C- and X-bands. Modification of the calculation to take into account the larger scale structure of the sea surface yields reasonable agreement for horizontal polarization at P- and L-bands, but is less successful for the cross-polarized and horizontal cross sections at C- and X-bands (see Wright, 1968).

Limitations and Possible Improvements

This model is limited mostly by the assumption of a slightly-rough surface which is true for Bragg waves. In the ocean when longer waves and swells are present, the Bragg waves are modulated, advected, and tilted by these longer waves. Thus, extension of the model is necessary to cover these cases, which leads to the composite model discussed below.

2.4 Composite-Surface Model

Background

The concept of the composite surface was investigated by Semyonov (1966), Barrick and Peake (1968), Bass et al. (1968) and Wright (1968). The model is formulated with the sea surface treated as one consisting of large swells on which are superimposed a smaller wave structure. The small structure or rough patch, is composed of short gravity and capillary waves which act as the main scatterers for Bragg scattering, while the swell tilts the scattering surface, thus modifying the scattering direction. The composite-surface model has withstood the test of experimental data for nearly two decades (Guinard et al., 1971).

Limitations and Possible Improvements

This seems to be the most widely accepted model for radar scattering. There exists many variants of this model with extensions through empirical

means or otherwise. Because the model is mostly valid in the range of small to moderate angles of incidence, it is especially important for wind/ocean scatterometry (Plant, 1986).

2.5 Wedge and Spilling Breaker Scattering Models

Background

The microwave scattering characteristics of the ocean surface appear to be largely explainable by a combination of slightly-rough, composite-surface, and specular models for a wide range of incidence angles, say from 0 to 70 degrees. At large incidence angles, the Bragg scattering model underestimates the radar cross section for horizontally polarized radiation, particularly at higher microwave frequencies as shown by Guinard and Daley (1970) and Guinard et al. (1971). At large incidence angles, a mechanism known as "wedge scattering" becomes important. This mechanism has been investigated by Kalmykow and Pustovoytenko (1976), Lewis and Olin (1980), and Lyzenga et al. (1983).

Wetzel (1977, 1986) gave a model for sea backscatter intermittency at extreme grazing angles (0 to 1 degree). He suggested in this model that at extreme angles, the primary microwave scatterers might lie at the peaks of breaking waves, moving with the group velocity of the dominant wave system and looking much the same at both horizontal and vertical polarizations. This model is able to explain the observed sharp transient bursts of backscatter having large cross sections for high resolution radars when viewing breaking waves at low grazing angles (see Lewis and Olin, 1980).

Limitations and Possible Improvements

The wedge and spilling wave models both try to account for the scattering due to steep and breaking waves at small grazing angles. Unfortunately, because of the transient nature of these waves and with the structurally different forms they may take, it is difficult to establish a deterministic model for them. One hopes to construct a statistically meaningful model to give an estimate of, say the amount of breaking waves or percentage of whitecaps within a certain area, and then estimate the sea clutter cross section under these conditions.

2.6 Potential Payoff of Research

It is clear that no single model can cover the full range of incidence angles from zero up to 90 degrees. Although the scattering models for small to moderate incidence angles are well developed, there is still much to be done for large incidence angle models, such as the wedge and spilling breaker models. All these models require environmental information, which vary from simple data, as in the GIT model, to more complicated input parameters as required for the wedge and spilling breaker models.

A complete description of the ocean surface should improve the estimation of sea clutter, but detailed ocean surface information is not likely to be available, and definitely not over a large portion of the open ocean. Thus, one hopes for some model for the ocean surface, which can give an accurate description of the ocean surface; given, say, the wind field in the area of interest. This ocean wave model could be used to improve the existing sea clutter models. Some of the plans for possible improvements and a simple

example are given in later sections. The most important aspect of this approach in combining an ocean wave model with a sea clutter model is that an accurate hybrid model is obtained that has predictive capability. This predictive power of the combined model should be valuable for planning and deployment of forces.

Recent research indicates that a number of atmospheric variables can also affect sea clutter. Some of these variables are atmospheric stability, and possibly sea surface temperature (Thompson et al., 1983; Keller et al., 1985). Researchers in the Frontal Air-Sea Interaction Experiment Workshop (FASINEX) have reported up to a 5db difference in backscatter signal strength across a front with 2.5 degrees centigrade temperature difference at low wind. Other effects, such as atmospheric ducting, should also be of interest. Snyder (1984), for example, presented a sea clutter model which is a union of classical one-dimensional ray-optics propagation with a semi-empirical normalized sea clutter cross section model not originally intended for application for ducting. Thus, in these cases, the air-sea interaction dynamics may need to be included in an even higher level sea clutter model.

From an operational viewpoint, if the ocean surface can be measured in real time, such as through the means of some surface-based remote sensors, the sea clutter model can be used for nowcasting of sea clutter. This can pave the way to sea clutter cancellation and can enhance other critical areas, such as improving the radar sensitivity by lowering the clutter threshold while maintaining a low false alarm rate for certain radar scan areas.

3. OCEAN WAVE MODELS

3.1 Background

A surface wave field evolves in space and time and is governed by the basic transport or energy balance equation for the two-dimensional wave spectrum $F(f, \theta ; x, t)$, which is a function of wave frequency f, direction θ, position x, and time t:

$$\frac{\partial F}{\partial t} + \mathbf{v} \cdot \nabla F = S \equiv S_{in} + S_{nl} + S_{ds} \tag{1}$$

Here $v = v(f, \theta)$ is the appropriate group velocity, and the net source function S is the sum of the wind input S_{in}, the nonlinear transfer by resonant wave-wave interactions S_{nl}, and the dissipation S_{ds}.

Most ocean wave models in use today compute the full two-dimensional wave spectrum by numerical integration of equation (1), or some approximation of it. The models differ mostly in the form assumed for the source function S. Depending on the different levels of sophistication in modeling the different source terms in (1), wave models are classified into first, second, or third generation models and with some sub-classifications and overlaps (SWAMP, 1985; Komen, 1987).

In the so-called first-generation models, the input source function is generally represented by,

$$S_{in} = A + BF, \tag{2}$$

where A represents an excitation mechanism such as that proposed by Phillips (1957) and BF corresponds to Miles' (1957) linear feedback mechanism. In this model, each spectral component evolves essentially independently of all other components in accordance with the linear input source function (2) until it approaches its limiting saturation level, which is again defined independently of the energy in other spectral components by a universal equilibrium distribution. Thus, nonlinear effects are considered unimportant.

In second-generation models, the independent evolution of individual wave components is effectively prevented by the coupling through the nonlinear energy transfer. However, either the spectral shape is predetermined (with parametric models) or the source functions and, in particular, the nonlinear source function are treated empirically.

In SWAMP, it was demonstrated that the second-generation models showed some improvement over the first-generation models, but have not shown any significant improvement over well-tuned first-generation models. A third-generation model which directly computes the nonlinear transfer has been developed (Hasselmann, 1987) and apparently has none of the limitations of the first- and the second-generation models although it is computationally more intensive.

3.2 A Spectral Ocean Wave Model: DWAVE

Most of the spectral ocean wave models give essentially the same type of outputs, for example, the significant wave height (mean period and mean direction), the swell height (mean period and mean direction), one- and two-dimensional wave spectra at grid points within the computational domain. Because the primary interest of this study is to investigate the effect of better environmental data on sea clutter estimation and not on evaluating various ocean wave models, we limit our scope to one ocean wave model and examine its effects on sea clutter estimation.

A deep ocean wave model DWAVE by Offshore & Coastal Technologies, Inc. (OCTI) has been chosen because it can be run on a small computer, such as the Hewlett Packard Model 9020, as opposed to almost all other wave models which require large computers. Being able to run the wave model on a small machine is important because of the large number of runs one has to perform in order to study the many possible environmental effects on the sea clutter models. However, DWAVE has been evaluated by Pickett et al. (1987) and found to perform well as compared to the "larger" models.

According to OCTI, DWAVE represents the state-of-the-art in the present understanding of wave generation (Resio, 1986). It is the first discrete-spectral model to be based on an f^{-4} equilibrium range formulation, as supported by many field experiments (Toba, 1978; Forristall, 1981; Kahma, 1981; Kitaigorodskii, 1983). It is consistent with energy conservation in the equilibrium range, similar to the third-generation model, as calculable from the complete or reduced Boltzmann integrals. The fetch-growth characteristics of DWAVE are similar to the JONSWAP relationships, i.e., wave energy increases linearly with fetch; and the duration-growth characteristics are roughly similar to those of Resio (1981) and the Navy's Spectral Ocean Wave Model (SOWM).

3.3 Limitations of DWAVE

DWAVE currently has a 16-direction band representation of the two-dimensional spectrum. Higher angular resolution of the 2D spectrum is possible and is limited only by the available computer memory. Similarly, this limitation applies for the frequency resolution of the model. However, the accuracy of the spectral densities for frequencies higher than 1 to 2 Hz has not been evaluated. Because the Bragg waves are at a much higher frequency range than that, it may be necessary to model the higher frequency waves. Furthermore, the swell or wave height and direction are important parameters because they affect the behavior of the higher frequency waves.

The ocean wave model can provide a wealth of information about the ocean surface that is relevant to sea clutter estimation. Because the required input to the ocean wave model is the wind field over the area, the accuracy of the ocean wave model also depends on the accuracy of the wind input. In cases where the wind input is from an atmospheric model, the accuracy of that particular model has to be taken into account also.

4. HYBRID MODEL DEVELOPMENT

Some of the sea clutter models mentioned in Section 2 can easily be adapted to accept the output from the ocean wave model. A number of these improvements may seem obvious, but many of them have not been tested or verified. In this section, an overall plan is given which outlines the approach in developing a hybrid ocean wave and sea clutter model. Some of the tasks that have been accomplished to date are also documented below.

4.1 Overall Plan

The overall plan for developing a hybrid model is depicted in the flow chart in Figure 5. The input to the hybrid model is the wind field which can be from a variety of sources. If a prediction is adequate, the wind field can be obtained from the prediction of a wind field model. On the other hand, if surface-based remote sensors are available, such as from a wind profiler network, then the actual measured wind can be used.

The flow chart shows the three possible methods for inter-connecting the outputs of the ocean wave model with the sea clutter model(s). The first and the simplest method is that the wave model gives the significant wave height and direction at each grid point of the area being calculated. The grid spacing over the computational domain of the ocean wave model is variable, so it can range from a scale of meters to thousands of kilometers provided that the deep water wave and other appropriate assumptions are satisfied.

Ideally, using a full one-dimensional wave spectrum together with a sea clutter model (e.g., the slightly-rough model) will be a better method to calculate the radar backscatter cross section. As mentioned before, the ocean wave model does not give reliable spectral components at high frequencies. In the second method, one can fit a high frequency "tail" to the 1-D spectrum given by the ocean wave model, e.g., an equilibrium range spectrum (Kitaigorodskii, 1983), so that the overall spectrum comprises an estimate of the full one-dimensional spectrum.

Similar to the one-dimensional spectrum "patching" of a high frequency range, the third method comprises adding high frequency tails to a two-dimensional wave spectrum (in each direction of interest). This method further improves the spatial estimation of high or low sea return areas. This method is more involved than the previous two, but with the dramatic increase in computational power, even for small computers, this method may be quite feasible.

The above three levels of improvement in environmental input constitute the approach for integrating the ocean wave model with existing sea clutter models. As with any model, the hybrid model needs to be verified by data. The data needed for verification are scarce because few radar tests are conducted with comprehensive records of relevant environmental factors. In the case for sea clutter studies, not only are the local factors needed, but the conditions around the radar site are also critical and this area may be many miles around the site. One possible data set is from Trizna (1987) collected during FASINEX. The possibility of setting up specific experiments in cooperation with other research facilities is also being considered.

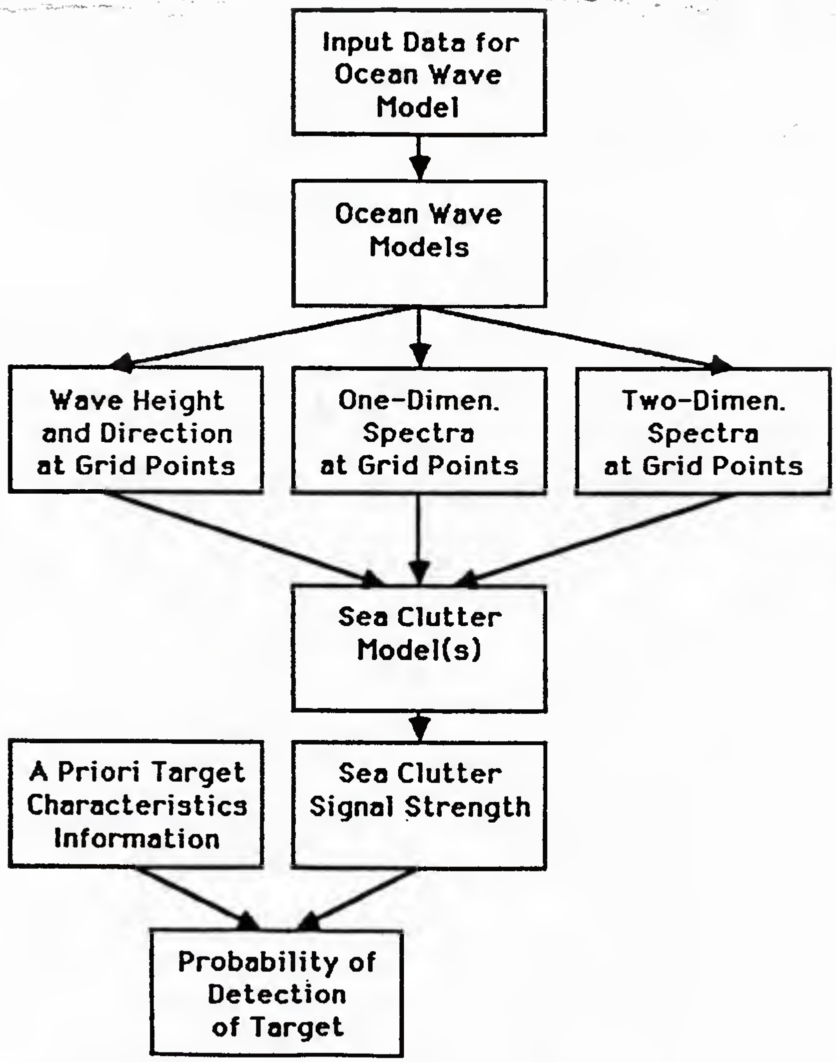

Figure 5 Research Plan Flow Chart.

Some additional features of DWAVE are being investigated. This particular ocean wave model has a double zooming capability, i.e. the model can zoom in twice on a specific region of the computational domain. One possible application of this double zooming feature is that it may be possible to first compute the global/regional wave field and then zoom in on a specific area which is of special interest and is of the order of the scanning range of a particular radar.

With the proper sea clutter model(s), the sea clutter signal strength can be calculated. Then if one knows a priori the radar cross section of a target, it may be possible to decide whether such a target can be detected given the necessary environmental conditions. Furthermore, the probability of detection of the target can be calculated when the sea clutter background signal and the target signal levels are known. This study concentrates on the calculation of sea clutter signal strength only.

4.2 High Resolution/Doppler Radars

A number of radars currently being deployed have high or variable resolution and Doppler capabilities. High resolution radars apparently are more susceptible to sea spikes or spiky sea clutter (Lewis and Olin, 1980). One theory is that because the high resolution radar views a very small area of the ocean surface, the sea return is highly correlated to the area being scanned. If it happens that the radar is looking at a breaking wave or a very steep wave with its front face pointing at the radar, the radar would receive a strong backscatter signal which may be due to a combination of specular, wedge, and Bragg scattering. In some cases, the sea spikes may be mistaken as point targets by the radar detection system.

The ocean wave model does not give information on the percentage of breaking waves or whitecaps. This information or an oceanic whitecap coverage model can be added to the ocean wave model based on some recent findings, such as those of Ochi and Tsai (1983), and Huang et al. (1986). Although these models can only give statistical results on whitecaps or breaking waves, they can be invaluable especially when such information is critical to the operation of high resolution radars.

A Doppler radar can detect the Bragg scatter phase velocity, the ocean wave orbital velocity, Stokes drift, and the wind drift. Trizna (1985) showed that these quantities might affect the Doppler spectral characteristics of radar sea scatter for low grazing angles. He presented a model to account for the spectral shift due to the various velocity contributions. The model uses many parameters which can readily be calculated from the ocean wave model. It will be interesting to see how well Trizna's model will do using the ocean wave model as the input. Unfortunately, Doppler radar data with environmental support data are also difficult to find. Various channels are being explored to collect Doppler radar data, such as from a Doppler meteorological radar.

4.3 A Specific Example of the Hybrid Model

The GIT model is currently running on a HP9020 computer at the Naval Environmental Prediction Research Facility (NEPRF). The ocean wave model DWAVE is also running on the same computer. Each model has been checked and verified by sample data sets and is running properly. Because of the

simplicity of the GIT model, the output is close to real time once the required parameters are given. The execution time for DWAVE is a function of the number of grid points in the computational domain.

Test cases were performed to examine the simplest form of the hybrid model. Some sample output data from the ocean wave model were used to drive the GIT sea clutter model. The environmental data used in this simple hybrid model were the significant wave height and wind or wave direction. A fictitious radar was assumed operating at 9.4 GHz (X-band), 0.1 us pulse width, 2.5 degree 3db beamwidth, and at 75 ft. above sea level.

The ocean wave model used actual interpolated NOAA wind information over the northern Atlantic from March 4, 1986 to March 11, 1986. The wind field was updated every six hours. A point within the computational domain was chosen to be the site of the fictitious radar. There was no special reason for this particular site except that it was situated in the open ocean and the wind and wave directions (directions are in vector form) were not always the same according to the ocean wave model. The distance between grid points was chosen to exceed the maximum range of the radar so that the wave field calculated from the ocean wave model was representative of the area scanned by the radar to keep the test case simple.

Two sample calculations of the radar clutter signal level are presented here to illustrate the effect of using either the wind direction or wave propagation direction for the GIT sea clutter model. In Figure 6, the wind direction (blowing from left to right) is used in the GIT model, so the sea echo is strongest in the upwind direction. In this particular case, the waves were propagating from right to left according to DWAVE. Thus, if the wave direction is used instead, the sea echo is strongest in the "upwave" segment as shown in Figure 7. Note that the wave height (3.8m in this case) given by the wave model was used in both figures. In other words, these two cases are mirror images of each other. These two examples are obviously extreme cases, but they illustrate the importance in choosing the correct environmental data. It is known that there is a lag in the wave propagation direction whenever the wind direction changes. Because it is mainly the waves that give rise to the sea clutter, it is most likely that the wave direction is the more relevant parameter. One may argue that the short waves or Bragg waves respond more quickly to changes in wind direction and the wind direction should be used instead. However, the larger waves and also the swells, which do not respond readily or strongly to the wind direction, influence the shorter waves. Hence, maybe some weighting should be done to account for these effects.

Various other aspects of this simple model will be investigated. For example, if one chooses to reduce the grid size of the ocean wave model, so that the radar actually scans in an area with more than one single grid point, then more information about the ocean would be available. It is likely that more environmental data, even for a simple hybrid model, will improve the estimation of sea clutter.

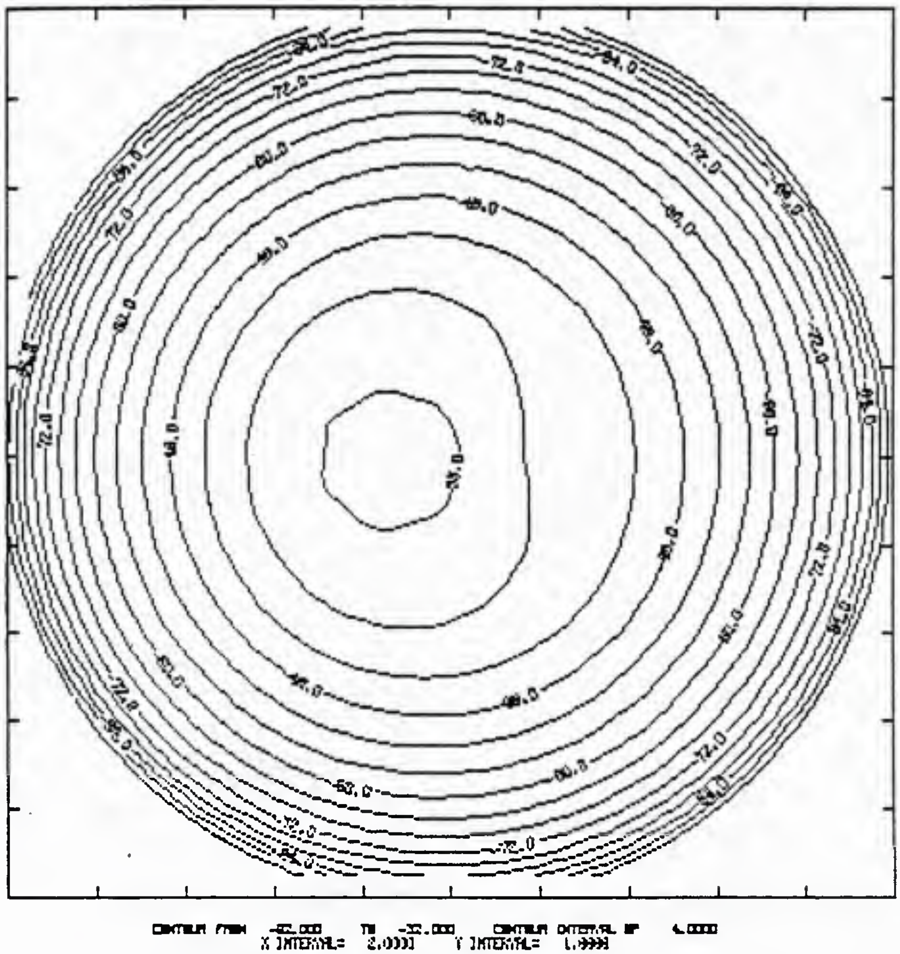

Figure 6 Sea Clutter Level in db, radar site at center. Contours in steps of -4db, first contour (near center) is -36db. Wind is from left to right. Distance between tic marks is 2 naut. miles.

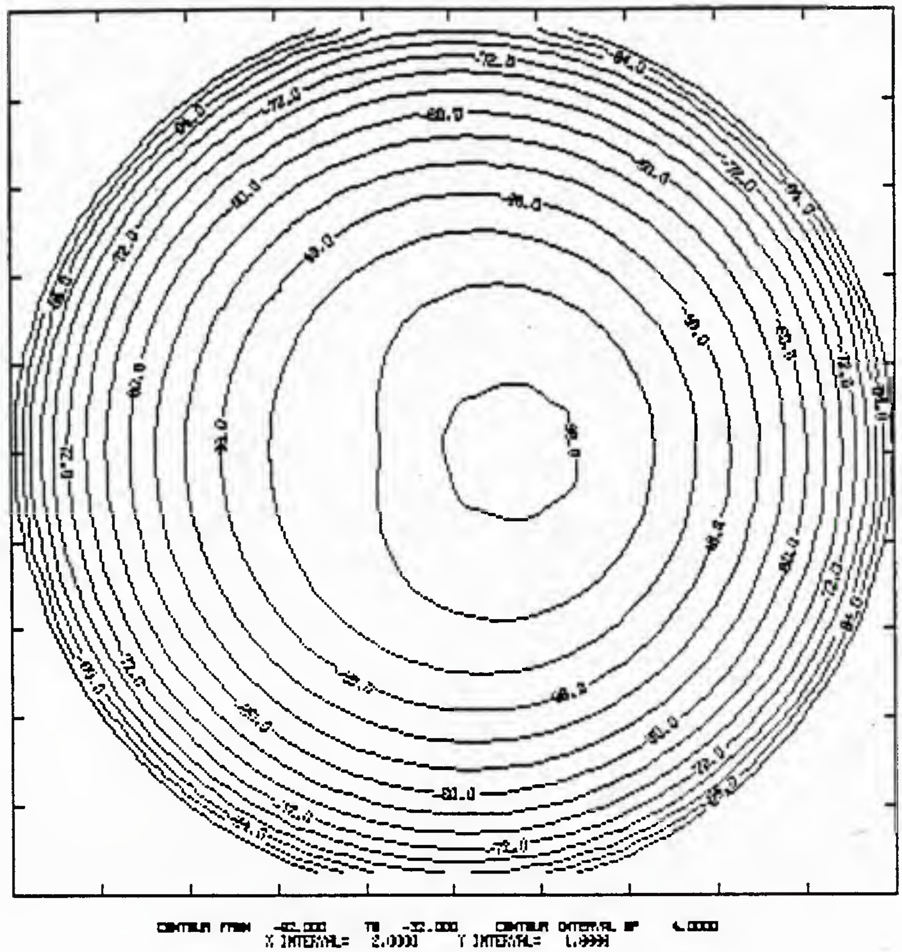

Figure 7 Sea Clutter Level in db, radar site at center. Contours in steps of -4db, first contour (near center) is -36db. Waves propagating from right to left. Distance between tic marks is 2 naut. miles.

5. SUMMARY AND RECOMMENDATIONS

5.1 Summary

Much work has been done on radar designs to reduce sea clutter, such as using different polarizations, multiple frequencies, special filters, signal processing techniques, etc.. A number of these techniques have been proven successful under certain conditions (Ward and Watts, 1985). However, it is necessary to understand what are the basic factors which cause the sea clutter in order to establish any type of model or signal processing technique for it. Many existing models give reasonable results over limited angles of incidence. A combination of these models may seem to be a good compromise. However, very little has been done in isolating the environmental factors involved.

This study thus far focuses on the effects of a more complete knowledge of the sea surface in estimating sea clutter. From the simple examples given in Section 4.3, it is clear that even a simple choice in direction can make a large difference in the sea clutter signal. There are other factors which one may consider, such as the different propagation directions between swells and gravity waves, the spectral content of the waves, and the whitecap coverage. These factors are known to affect radar backscatter and in many models have not been taken into account because there have not been ways to measure or calculate them. An ocean wave model with additional modifications can provide information on these factors which can lead to improvements in sea clutter estimation.

5.2 Recommendations

The following recommendations are made:

1. Sea clutter data need to be collected with comprehensive environmental information. This may encompass cooperative efforts among various Navy research facilities and/or contractors. This should be one of the highest priorities in sea clutter research because even the simplest hybrid model needs to be verified. Depending on the funding situation, it is desirable to have both laboratory and field experiments. Laboratory experiments have well-controlled conditions and are best-suited to isolate the myriad of factors which affect radar sea backscatter and to develop instruments which can be used in the field.

2. Further research on the ocean wave model is needed to examine the possibility of patching or modeling a high frequency range for the 1-D and 2-D wave spectra and the effects on various sea clutter models. Another alternative is to measure the sea surface and the relevant environmental parameters directly. Other valuable information from the ocean wave model, which can be run independent of a central site, can be used for ship routing or calculating ship response.

3. There is a need to investigate the use of various surface-based remote sensors to provide information for either the ocean wave model or the sea clutter models. Hembree (1986) discussed numerous instruments that can be used to remotely monitor the atmosphere in the vicinity of an afloat platform. Some of these instruments, such as lidars or wind profilers, may be planned for future Navy ships and can provide appropriate information for various models.

4. There is a need to examine the integration of the various signal processing techniques with environmental information. For example, some sea clutter canceling schemes may need the position (the range and angle) of a high sea clutter region to adjust certain threshold values or filter coefficients. In the case of a Doppler radar, information on the Bragg wave phase speed or drift current may be needed for various target discrimination algorithms.

5. Although this study is currently aimed at the most important factor in sea echo -- the ocean surface, the atmospheric conditions must be considered also, especially for long-range radars. Some interesting questions may be: What are the effects of ducting on multiple beam Doppler radars ? If ducting is important for these radars, how does ducting affect the sea clutter background ?

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